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Observational evidence for a correlation between jet power and black hole spin

Ramesh Narayan★ and Jeffrey E. McClintock★

Harvard–Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA

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ABSTRACT

We show that the 5-GHz radio flux of transient ballistic jets in black hole binaries correlates with the dimensionless black hole spin parameter a_* estimated via the continuum-fitting method. The data suggest that jet power scales either as the square of a_* or as the square of the angular velocity of the horizon $\Omega_{\rm H}$. This is the first direct evidence that jets may be powered by black hole spin energy. The observed correlation validates the continuum-fitting method of measuring spin. In addition, for those black holes that have well-sampled radio observations of ballistic jets, the correlation may be used to obtain rough estimates of their spins.

Key words: accretion, accretion discs – black hole physics – binaries: close – ISM: jets and outflows – X-rays: binaries.

1 INTRODUCTION

Accreting black holes (BHs), both supermassive and stellar mass, are commonly observed to produce powerful relativistic jets (Zensus 1997; Mirabel & Rodríguez 1999). Although there now exists a wealth of data and many detailed models, the mechanism that powers these jets remains a mystery.

The popular idea that jets are powered by the BH goes back to the work of Penrose (1969), who showed that a spinning BH has free energy. Blandford & Znajek (1977) proposed a plausible mechanism whereby this free energy could be used to power an astrophysical jet. They suggested that magnetic fields in the vicinity of an accreting BH would be twisted as a result of the dragging of space–time by the rotating BH. The twisted field lines will carry away energy from the BH, producing an electromagnetic jet. The broad outlines of this model have been confirmed in numerical simulations (e.g. Tchekhovskoy, Narayan & McKinney 2011).

While a connection between BH spin energy and relativistic jets is theoretically very appealing, there has been no direct observational evidence for such a link. This is because, until recently, there was no BH with a believable measurement of the dimensionless spin parameter $a_* \equiv cJ/GM^2$, where M and J are the mass and angular momentum of the BH. The situation has now changed. Methods are now available – one in particular, the continuum-fitting (CF) method[1] (Zhang, Cui & Chen 1997; Gierliński, Maciołek-Niedźwiecki & Ebisawa 2001; Shafee et al. 2006; Davis, Done & Blaes 2006; McClintock et al. 2006) – that have enabled us to make plausibly reliable measurements of a_* for several stellar mass BHs. With this sample of spin measurements, we are now in a position to test whether jet power is related to BH spin. Such a test is the goal of this Letter.

In Section 2, we describe our sample of stellar mass BHs and collect together the relevant observational data on BH spins and jet power. In Section 3, we plot radio power against BH spin and demonstrate that there is a significant correlation between the two quantities. We summarize and discuss in Section 4.

2 THE DATA

2.1 BH sample and spin estimates

The CF method (see McClintock et al. 2011, for a brief review) fits the X-ray continuum spectrum of an accreting stellar mass BH using the classic relativistic thin-disc model of Novikov & Thorne (1973). The spectral fit gives an estimate of the radius of the inner edge of the accretion disc. The BH spin parameter a_* is then obtained by assuming that the disc edge is located at the innermost stable circular orbit (ISCO) of the Kerr metric. The CF method has been developed in detail over the last several years and has been shown to produce consistent results when multiple independent observations of the same source are available (e.g. Steiner et al. 2009, 2010). In addition, numerical simulations have provided support for a crucial assumption of the model, namely that the disc inner edge is close to the ISCO (Shafee et al. 2008; Penna et al. 2010; Kulkarni et al. 2011; Noble et al. 2011).

The spins of the BH primaries in nine BH binaries (BHBs) have been measured using the CF method (Gou et al. 2011; McClintock et al. 2011). Five of these BHBs, namely A0620−00, XTE J1550−564, GRO J1655−40, GRS 1915+105 and 4U 1543−47, are transient systems (Remillard & McClintock 2006).

★E-mail: rnarayan@cfa.harvard.edu (RN); jmcclintock@cfa.harvard.edu (JEM)

[1] A second method, based on modelling the relativistically broadened X-ray iron Kα line, is not considered in this Letter (see Section 4 for a discussion).

Table 1. Parameters of transient BHBs in the sample.

BH Binary	a_*	M ($\mathrm{M}_\odot$)	D (kpc)	i (°)	$(S_\nu)_{\max,5\,\mathrm{GHz}}$ (Jy)	$S_0(\gamma = 2)$ (Jy)	References
A0620−00	0.12 ± 0.19	6.61 ± 0.25	1.06 ± 0.12	51.0 ± 0.9	0.203	0.145	1, 6, 7
XTE J1550−564	0.34 ± 0.24	9.10 ± 0.61	4.38 ± 0.50	74.7 ± 3.8	0.265	0.859	2, 6, 8
GRO J1655−40	0.7 ± 0.1	6.30 ± 0.27	3.2 ± 0.5	70.2 ± 1.9	2.42	7.74	3, 4, 6, 9, 10
GRS 1915+105	0.975 ± 0.025	14.0 ± 4.4	11.0 ± 1.0	66.0 ± 2.0	0.912	2.04	5, 6, 11, 12
4U 1543−47	0.8 ± 0.1	9.4 ± 1.0	7.5 ± 1.0	20.7 ± 1.5	$>1.16 \times 10^{-2}$	$>4.31 \times 10^{-4}$	3, 6, 13

References: (1) Gou et al. (2010); (2) Steiner et al. (2011); (3) Shafee et al. (2006); (4) Davis et al. (2006); (5) McClintock et al. (2006); (6) Özel et al. (2010); (7) Kuulkers et al. (1999); (8) Hannikainen et al. (2009); (9) Hjellming & Rupen (1995); (10) Hannikainen et al. (2000); (11) Rodriguez et al. (1995); (12) Fender et al. (1999) and (13) Park et al. (2004).

These five systems have low-mass secondaries and undergo mass transfer via Roche lobe overflow. They are of primary interest to us because during outburst, as they approach the Eddington limit, they produce ballistic jets (Section 2.2). The measured BH spin values a_* and masses M, along with distances D and binary inclination angles i, are listed in Table 1. In the case of A0620−00 and XTE J1550−564, the error estimates on the spins are taken from the original papers (Gou et al. 2010; Steiner et al. 2011). The other three spins were measured in the early days of the CF method (Shafee et al. 2006; Davis et al. 2006; McClintock et al. 2006), and we have doubled the published error estimates.

An additional four stellar mass BHs have spin estimates: LMC X-3 (Davis et al. 2006), M33 X-7 (Liu et al. 2008, 2010), LMC X-1 (Gou et al. 2009) and Cyg X-1 (Gou et al. 2011). These are persistent BHBs (Remillard & McClintock 2006) which have high-mass companion stars and undergo mass transfer via winds. Also, they do not show the kind of transient behaviour seen in the previous five objects and are generally understood to belong to a different class. We ignore them in this study.

2.2 Jet radio power

Fender, Belloni & Gallo (2004) identified a number of systematic properties in the radio emission of BHB jets. They showed that there are two kinds of jets associated with specific spectral states of the X-ray source. The first type of jet is observed in the hard spectral state as a steady outflow. This jet is observable only out to a few tens of au and is apparently not very relativistic. The second and far more dramatic jet, which is central to this Letter, is launched when a BHB with a low-mass secondary undergoes a transient outburst (Fender et al. 2004). This powerful transient jet usually appears near (or soon after) the time of outburst maximum, as the source switches from its initial hard state to a soft state via the 'steep power-law' (SPL) state, a violently variable state characterized by both strong thermal and power-law components of emission (Remillard & McClintock 2006). Transient jets manifest themselves as blobs of radio (and occasionally X-ray) emitting plasma that move ballistically outwards at relativistic speeds ($\gamma_{\rm jet} > 2$). Because these pc-scale jets resemble the kpc-scale jets seen in quasars, BHBs that produce them are called microquasars (Mirabel & Rodríguez 1999).

Ballistic jet ejection occurs at a very specific stage during the spectral evolution of a given system (Fender et al. 2004). As most clearly demonstrated for the prototype microquasar GRS 1915+105 (Fender & Belloni 2004), this stage appears to correspond to the inward-moving inner edge of the accretion disc reaching the ISCO, which results in a shock or some other violent event that launches the large-scale relativistic jet. In this scenario, it appears reasonable that the jet is launched within a few gravitational radii and hence plausible that the spin energy of the BH could power the jet. In contrast, the steady jet in the hard state is thought to originate much further out at $\sim$10–100 GM/c^2 (Markoff, Nowak & Wilms 2005) where the effects of spin are relatively weak. Another virtue of the ballistic jets for our purposes is that they occur at a sharply defined luminosity (i.e. near Eddington) compared to the hard state steady jets, which occur over a wide range of luminosity. Ballistic jets are thus better 'standard candles'. For these reasons, in this Letter, we restrict our attention to ballistic jets from transient low-mass BHBs.

A typical ballistic jet blob is initially optically thick and has a low radio power. As the blob moves out and expands, the larger surface area causes its radio power to increase. This continues until the blob becomes optically thin, after which the flux declines rapidly. The overall behaviour is generally consistent with an expanding conical jet (e.g. Hjellming & Johnston 1988).

Fig. 1 shows the peak radio flux $(S_\nu)_{\max}$ versus ν observed at different radio frequencies ν for four of the five transient BHBs in our sample. The radio light curves of these four systems were monitored with good time resolution, allowing us to obtain reasonably accurate estimates of the peak fluxes. The top left-hand panel shows data for two separate outbursts of GRS 1915+105 (the solid and open circles correspond, respectively, to the outbursts studied by Rodriguez et al. 1995 and Fender et al. 1999). The two lines are fits

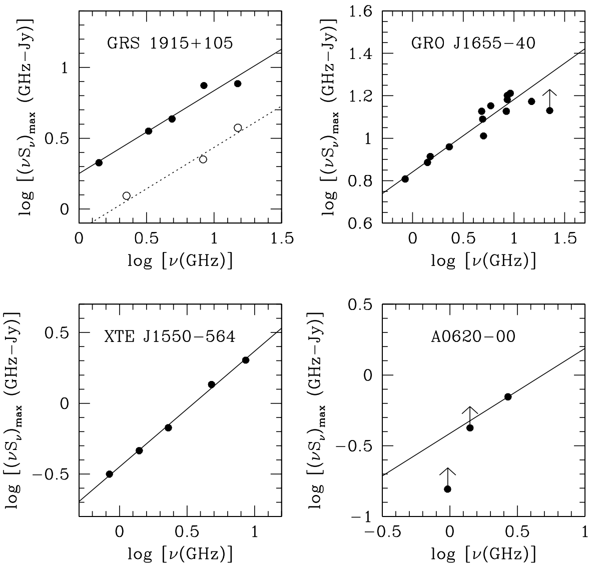

Figure 1. Plot of the maximum observed radio power $(\nu S_\nu)_{\max}$ as a function of frequency ν for transient ballistic jet outbursts in four BHBs. Two separate outbursts are shown for GRS 1915+105. Best-fitting lines (two separate ones in the case of GRS 1915+105) are indicated, except in the case of A0620−00 where the line slope is fixed at 0.6 (or $\alpha = -0.4$).

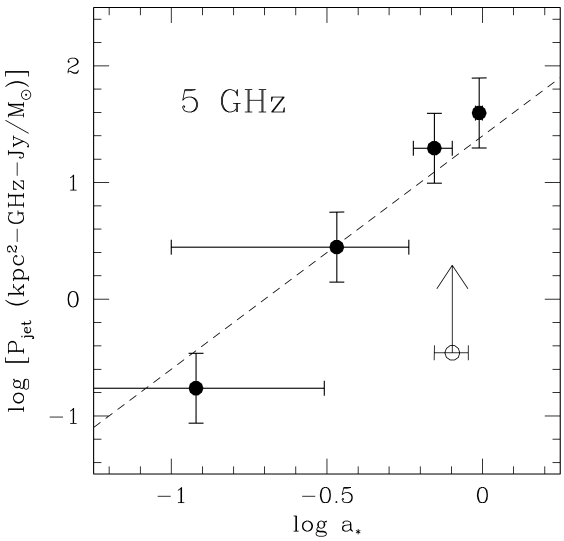

Figure 2. Plot of the jet power $P_{\rm jet}$ as estimated from the maximum radio flux of ballistic jets (equation 1) versus the measured spin parameter of the BH a_* for the transient BHBs in our sample. Solid circles correspond to the first four objects listed in Table 1, which have high-quality radio data, and the open circle corresponds to 4U 1543−47, which has only a lower limit on the jet power. The dashed line corresponds to $P_{\rm jet} \propto a_*^2$, the theoretical scaling derived by Blandford & Znajek (1977). The data suggest that ballistic jets derive their power from the spin of the central BH.

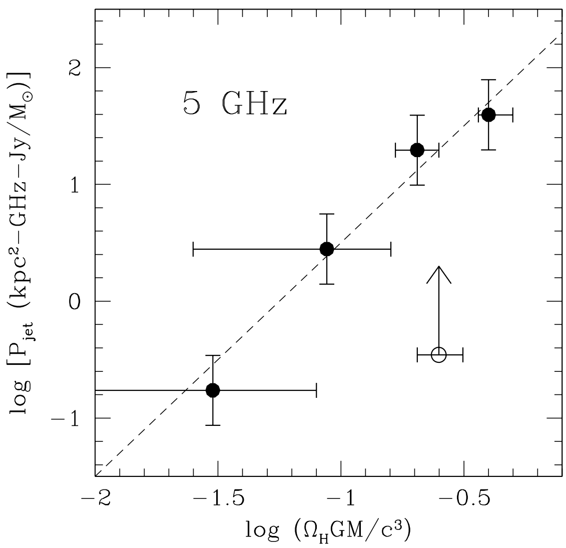

Figure 3. Similar to Fig. 2, but showing the angular velocity of the BH horizon $\Omega_{\rm H}$ along the abscissa. The dashed line corresponds to $P_{\rm jet} \propto \Omega_{\rm H}^2$ (Tchekhovskoy, Narayan & McKinney 2010).

to the respective data and have a slope of 0.59; writing the spectrum as $S_\nu \propto \nu^\alpha$, the fit corresponds to $\alpha = -0.41$. The top right-hand panel combines the observations of Hjellming & Rupen (1995) and Hannikainen et al. (2000) during an outburst of GRO J1655−40. The best-fitting line corresponds to $\alpha = -0.66$.[2] The lower two panels show data for XTE J1550−564 ($\alpha = -0.18$; Hannikainen et al. 2009) and A0620−00 (Kuulkers et al. 1999). For the latter source, we do not have enough data points to determine the slope; the line in the plot corresponds to $\alpha = -0.4$, the average spectral index of the other three BHBs. In order to enable a fair comparison of the different objects, we use the fitted lines in the four panels to estimate the peak fluxes $(S_\nu)_{\rm max}$ at a standard frequency of 5 GHz. These 5-GHz peak flux values are listed in Table 1.

While each of the above four objects was densely observed in radio during one or more transient outbursts, 4U 1543−47 was unfortunately not monitored well at radio frequencies during any of its several outbursts. The only radio data we know of when the source was bright are those for the 2002 outburst summarized in Park et al. (2004). The strongest radio flux was 0.022 Jy at 1.026 75 GHz. Assuming $\alpha = -0.4$, this gives a flux of 0.0116 Jy at 5 GHz (or only 0.000 43 Jy if one corrects for beaming with $\gamma_{\rm jet} = 2$). We list this result separately in Table 1 and plot it as a lower limit in Figs 2 and 3 because of the sparse radio coverage. In addition, there was an anomaly in the 2002 X-ray outburst of this source.

The anomalous behaviour of 4U 1543−47 is apparent by an inspection of figs 4–9 in Remillard & McClintock (2006), which summarize in detail the behaviour of six BH transients scrutinized by *RXTE*. In panel b of these figures, which displays light curves of the PCA model flux coded by X-ray state, one sees that only 4U 1543−47 failed to enter the SPL state (green triangles) near the peak of its outburst, i.e. at the time of the radio coverage reported by Park et al. Rather, it remained locked in the thermal state (red crosses) after its rise out of the hard state. This behaviour contrasts sharply with the behaviour of the other five transients which displayed the strongly Comptonized SPL state during both the late phase of their rise to maximum and during their early decay phase. Thus, because of (1) the sparse radio coverage of 4U 1543−47 and (2) the failure of the source to transition out of the jet-quenched thermal state (Gallo, Fender & Pooley 2003) to the SPL state (which is closely associated with the launching of ballistic jets), we treat the maximum observed flux of 0.022 Jy as a lower limit. Finally, in sharp contrast to our finding, we note that figs 5 and 6 in Fender et al. (2004) indicate a very high jet power for 4U 1543−47. We are unsure how they arrived at their result, but suspect it was based on infrared data and their equipartition model (see Section 4). If so, an extension of the present work to infrared data might be worthwhile.

To measure jet power, we scale the 5-GHz peak flux of each BHB by the square of the distance to the source D. We also divide by the BH mass M since we expect the power to be proportional to M (this scaling is not important since the range of masses is only a factor of ∼2). We thus obtain from the radio observations the following quantity, which we treat as a proxy for the jet power:

$$P_{\rm jet} \equiv D^2(\nu S_\nu)_{\rm max,5\,GHz}/M. \quad (1)$$

It is hard to assess the uncertainty in the estimated values of $P_{\rm jet}$. There is some uncertainty in the values of D and M, but these are not large. Potentially more serious, the radio flux may not track jet power accurately. For instance, the properties of the ISM in the vicinity of the BHB may play a role and are likely to vary from one object to another. Also, the energy released in these roughly Eddington-limited events will vary (e.g. see GRS 1915+105 in Fig. 1). Below, we arbitrarily assume that the uncertainty in $P_{\rm jet}$ is 0.3 in the log, i.e. a factor of 2 each way.

3 JET POWER VERSUS BH SPIN

Fig. 2 shows jet power $P_{\rm jet}$ plotted against BH spin parameter a_* for the five transient BHBs in our sample. The data are taken from Table 1. The dashed line has a slope of 2, motivated by the theoretical

[2] In the case of GRO J1655−40, the 22-GHz observations did not cover the peak of the light curve. Hence, this point is shown as a lower limit. Similarly, in A0620−00, the peak was not observed at 0.962 and 1.14 GHz.

scaling, $P_{\rm jet} \propto a_*^2$, derived by Blandford & Znajek (1977). The data points agree remarkably well with this theoretical prediction.

Blandford & Znajek (1977) assumed a slowly spinning BH: $a_* \ll 1$. Tchekhovskoy et al. (2010) obtained a more accurate theoretical scaling which works up to spins fairly close to unity: $P_{\rm jet} \propto \Omega_{\rm H}^2$, where $\Omega_{\rm H}$ is the angular frequency of the BH horizon, $\Omega_{\rm H} = a_*(c^3/2GM)/(1+\sqrt{1-a_*^2})$. Fig. 3 shows a plot of $P_{\rm jet}$ versus $\Omega_{\rm H}$, with the dashed line corresponding to a slope of 2. The agreement is again very good.

We need to consider one additional effect: relativistic beaming. Assuming a typical jet Lorentz factor $\gamma_{\rm jet} = 2$ (Fender et al. 2004) and using the inclination angles i given in Table 1, we have corrected the values of $(S_\nu)_{\rm max,5\,GHz}$. The beaming-corrected radio fluxes S_0 (computed using the relations given in Mirabel & Rodríguez 1999 with the values of α given in Section 2.2) are listed in Table 1. The inferred jet power of A0620−00 (the leftmost point in Figs 2 and 3) decreases by a small factor, whereas the other three jet powers increase by a larger factor. As a result, the spread in $P_{\rm jet}$ among the four objects becomes ∼3.0 orders of magnitude, compared to ∼2.4 orders in Figs 2 and 3. Thus, allowing for beaming enhances the range of $P_{\rm jet}$ in the sources and solidifies further the connection between jet power and BH spin.

4 DISCUSSION

Since the correlations shown in Figs 2 and 3 are based on only four objects, one wonders whether we are merely seeing chance alignment of intrinsically uncorrelated data. The chief argument against this hypothesis is that a_* varies over the full allowable range of prograde spins, $\Omega_{\rm H}$ varies by more than a factor of 10 and $P_{\rm jet}$ varies by 2.4 orders of magnitude (or 3 orders of magnitude if one corrects for beaming assuming $\gamma_{\rm jet} = 2$). Also, the plotted points differ from one another by several standard deviations, which is not statistically likely. Therefore we conclude that the power of ballistic jets is most likely correlated with the spin of the accreting BH.

At the same time, and as a corollary, the strong apparent correlation validates the CF method of measuring spin. The CF method is based on a number of assumptions, most of which have been independently validated (see McClintock et al. 2011). The results presented here provide yet another validation. Caveats to the above conclusions include the small size of the sample, insufficient data on one object (4U 1543−47) and uncertainties on how well jet power and radio luminosity track each other.

The existence of a correlation between jet power and BH spin does not necessarily mean that the energy source for the jet is BH spin. The power could possibly be supplied by the accretion disc (Ghosh & Abramowicz 1997; Livio, Ogilvie & Pringle 1999). Since the binding energy of a particle at the ISCO increases with increasing a_*, the disc power increases with BH spin and this might cause the observed correlation. However, we note that the radiative luminosity of a thin accretion disc varies by only a modest factor with BH spin; the radiative efficiency $\eta = 0.061$ for $a_* = 0.12$ (the spin of A0620−00) and $\eta = 0.23$ for $a_* = 0.98$ (the spin of GRS 1915+105). If jet power scales similarly, and if radio luminosity is roughly proportional to jet power, we expect no more than a factor of 4 variation in the radio powers in our sample. Instead, we see a factor of ∼250–1000. Moreover, the observed spread is rather close to what is expected theoretically if jets are powered by BH spin. The evidence thus suggests that ballistic jets are powered directly by the spin energy of the accreting BH.

Based on the above arguments, we view our results as a confirmation of the Penrose–Blandford–Znajek mechanism of powering relativistic jets by BH spin energy. Theoretically, this mechanism depends on both the BH spin and the magnetic field strength at the horizon. The latter is believed to depend on the mass accretion rate $\dot{M}$ (e.g. Tchekhovskoy et al. 2011). Since ballistic jets are seen during a very specific phase of the evolution of a transient BHB, it is reasonable to assume that $\dot{M}$ (normalized by the BH mass) is roughly the same in different objects when they exhibit ballistic jets, or indeed in different ballistic jet episodes in the same object. This allows us to eliminate $\dot{M}$ from our analysis and to treat ballistic jets as 'standard candles', thereby making the comparisons shown in Figs 2 and 3 meaningful.

In addition to the CF method, a second method based on fitting the profile of the relativistically broadened Fe Kα line has been used to estimate BH spins (Reynolds & Nowak 2003; Miller 2007). In this Letter, we opt to use only CF spin data for two reasons. (1) The Fe-line models are complex and therefore relatively less reliable. CF spins are obtained rather simply by modelling a dominant thermal disc component, while Fe-line spins require modelling the thermal disc plus a Compton component plus a disc reflection component, which includes the Fe Kα line. The Fe-line method furthermore requires characterizing a luminous corona of unknown geometry. (2) For several well-studied systems, the Fe-line method has generated widely inconsistent values of the spin parameter or shown to be strongly model-dependent (e.g. for Cyg X-1, see section 7.1 in Gou et al. 2011; for MCG-6-30-15, see Miller, Turner & Reeves 2009). The CF method, on the other hand, gives consistent results for multiple and independent observations of individual sources. For example, for the BHBs listed in Table 1 (excluding A0620−00), consistent results were obtained for ≈50 *RXTE* spectra (XTE J1550−564); two *ASCA* and 31 *RXTE* spectra (GRO J1655−40); one *ASCA* and five *RXTE* spectra (GRS 1915+105); and 34 *RXTE* spectra (4U 1543−47). The standout example is LMC X-3 with 411 spectra collected by eight X-ray missions over 26 years (Steiner et al. 2010).

After considering separately both ballistic and hard state steady jets, Fender, Gallo & Russell (2010) find no evidence for a correlation between jet power and BH spin. We have already given in Section 2.2 a plausible reason for the absence of evidence in the case of the steady jets. We now focus on rationalizing the very different results obtained by Fender et al. (presented in their section 2.2.1 and fig. 6) and ourselves for the ballistic jets. Our data sample (Table 1) is identical to their comparable sample (see the right-hand panel of their fig. 6). The only significant difference in data selection is that for GRO J1550−564, we use the new spin value of Steiner et al. (2011), $a_* = 0.34 \pm 0.24$, while they used the earlier Davis et al. (2006) limit of $a_* < 0.8$.

The substantial difference between our results and those of Fender et al. (2010) is, in the end, determined by the choice of the quantity used to represent jet power. We simply use the maximum observed flux density at 5 GHz expressed as a luminosity. Fender et al. compute jet power from the peak radio luminosity and the rise time of some particular synchrotron event. The authors clearly state that their approach 'is useful to provide lower limits on, and order-of-magnitude estimates of, jet power but is very susceptible to errors resulting from poor sampling of events, uncertainties in Doppler boosting, assumptions about equipartition, etc.' Their estimates of jet luminosity for three sources are given in table 1 of Fender et al. (2004), but it is not clear how the luminosities of A0620−00 and 4U 1543−47 were estimated. The authors further adopt a formula relating jet power to X-ray luminosity,

$\log_{10} L_{\mathrm{jet}} = c + 0.5(\log_{10} L_{\mathrm{x}} - 34)$, and estimate the normalization constant c in the preceding formula, which they treat as their proxy for jet power. In short, their proxy for jet power is heavily model-dependent and ours is model-independent.

The correlation shown in Fig. 2 can be used to obtain rough estimates of spin for any transient BH that has undergone a major outburst cycle and that has been closely monitored at radio wavelengths. For instance, radio observations of Nova Muscae 1991 (GRS 1124−68) by Ball et al. (1995) suggest a maximum 5-GHz radio flux ≈0.2 Jy. Assuming a distance $D \approx 6$ kpc and a typical BH mass $M \approx 8\,\mathrm{M}_{\odot}$ (Özel et al. 2010), we obtain $\log\,[P_{\mathrm{jet}}] \approx 0.65 \pm 0.3$. Fig. 2 then gives $a_* \approx 0.3$–0.6. In the case of GX 339−4, the brightest X-ray and radio outburst (Gallo et al. 2004) had a maximum 5-GHz flux of 0.055 Jy. Taking $D \approx 9$ kpc, $M \approx 8\,\mathrm{M}_{\odot}$ (Özel et al. 2010), we find $\log\,[P_{\mathrm{jet}}] \approx -0.25 \pm 0.4$ and $a_* \approx 0.2$–0.5. The latter estimate is consistent with the strict upper limit $a_* < 0.9$ derived by Kolehmainen & Done (2010) using the CF method with conservative assumptions.

These examples illustrate the importance of obtaining good radio coverage for all future transient BHBs, including especially the recurrent system 4U 1543−47. Those systems that have CF-based spin measurements will flesh out the correlations plotted in Figs 2 and 3. For the many other BH transients that lack a sufficiently bright optical counterpart and are therefore out of reach of the CF method, the radio data can either be used as a check on Fe-line measurements of spin or serve as our only estimate of spin.

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REFERENCES

Ball L., Kesteven M. J., Campbell-Wilson D., Turtle A. J., Hjellming R. M., 1995, MNRAS, 273, 722
Blandford R. D., Znajek R. L., 1977, MNRAS, 179, 433
Davis S. W., Done C., Blaes O. M., 2006, ApJ, 647, 525
Fender R., Belloni T., 2004, ARA&A, 42, 317
Fender R. P. et al., 1999, MNRAS, 304, 865
Fender R. P., Belloni T. M., Gallo E., 2004, MNRAS, 355, 1105
Fender R. P., Gallo E., Russell D., 2010, MNRAS, 406, 1425
Gallo E., Fender R. P., Pooley G. G., 2003, MNRAS, 344, 60
Gallo E., Corbel S., Fender R. P., Maccarone T. J., Tzioumis A. K., 2004, MNRAS, 347, L52
Ghosh P., Abramowicz M. A., 1997, MNRAS, 292, 887
Gierliński M., Maciołek-Niedźwiecki A., Ebisawa K., 2001, MNRAS, 325, 1253
Gou L. et al., 2009, ApJ, 701, 1076
Gou L., McClintock J. E., Steiner J. F., Narayan R., Cantrell A. G., Bailyn C. D., Orosz J. A., 2010, ApJ, 718, L122
Gou L. et al., 2011, ApJ, 742, 85
Hannikainen D. C., Hunstead R. W., Campbell-Wilson D., Wu K., McKay D. J., Smits D. P., Sault R. J., 2000, ApJ, 540, 521
Hannikainen D. C. et al., 2009, MNRAS, 397, 569
Hjellming R. M., Johnston K. J., 1988, ApJ, 328, 600
Hjellming R. M., Rupen M. P., 1995, Nat, 375, 464
Kolehmainen M., Done C., 2010, MNRAS, 406, 2206
Kulkarni A. K. et al., 2011, MNRAS, 414, 1183
Kuulkers E., Fender R. P., Spencer R. E., Davis R. J., Morison I., 1999, MNRAS, 306, 919
Liu J., McClintock J. E., Narayan R., Davis S. W., Orosz J. A., 2008, ApJ, 679, L37
Liu J., McClintock J. E., Narayan R., Davis S. W., Orosz J. A., 2010, ApJ, 719, L109
Livio M., Ogilvie G. I., Pringle J. E., 1999, ApJ, 512, 100
McClintock J. E., Shafee R., Narayan R., Remillard R. A., Davis S. W., Li L.-X., 2006, ApJ, 652, 518
McClintock J. E. et al., 2011, Classical Quantum Gravity, 28, 11, 114009
Markoff S., Nowak M. A., Wilms J., 2005, ApJ, 635, 1203
Miller J. M., 2007, ARA&A, 45, 441
Miller L., Turner T. J., Reeves J. N., 2009, MNRAS, 399, L69
Mirabel I. F., Rodríguez L. F., 1999, ARA&A, 37, 409
Noble S. C., Krolik J. H., Schnittman J. D., Hawley J. F., 2011, preprint (arXiv:1105.2825)
Novikov I. D., Thorne K. S., 1973, in Dewitt C., Dewitt B. S., eds, Black Holes (Les Astres Occlus). Gordon and Breach, Paris, p. 343
Özel F., Psaltis D., Narayan R., McClintock J. E., 2010, ApJ, 725, 1918
Park S. Q. et al., 2004, ApJ, 610, 378
Penna R. F., McKinney J. C., Narayan R., Tchekhovskoy A., Shafee R., McClintock J. E., 2010, MNRAS, 408, 752
Penrose R., 1969, Nuovo Cimento Rivista Serie, 1, 252
Remillard R. A., McClintock J. E., 2006, ARA&A, 44, 49
Reynolds C. S., Nowak M. A., 2003, Phys. Rep., 377, 389
Rodriguez L. F., Gerard E., Mirabel I. F., Gomez Y., Velazquez A., 1995, ApJS, 101, 173
Shafee R., McClintock J. E., Narayan R., Davis S. W., Li L.-X., Remillard R. A., 2006, ApJ, 636, L113
Shafee R., McKinney J. C., Narayan R., Tchekhovskoy A., Gammie C. F., McClintock J. E., 2008, ApJ, 687, L25
Steiner J. F., McClintock J. E., Remillard R. A., Narayan R., Gou L., 2009, ApJ, 701, L83
Steiner J. F., McClintock J. E., Remillard R. A., Gou L., Yamada S., Narayan R., 2010, ApJ, 718, L117
Steiner J. F. et al., 2011, MNRAS, 416, 941
Tchekhovskoy A., Narayan R., McKinney J. C., 2010, ApJ, 711, 50
Tchekhovskoy A., Narayan R., McKinney J. C., 2011, MNRAS, 418, L79
Zensus J. A., 1997, ARA&A, 35, 607
Zhang S. N., Cui W., Chen W., 1997, ApJ, 482, L155

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